In-band Full-duplex in Hand-held Applications: Analysis of Canceller Tuning Requirements

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***Abstract*—This paper investigates the impact of user-antenna interaction on transmit-to-receive (Tx-Rx) isolation in a hand-held In-band Full-duplex (IBFD) transceiver. Dynamic antenna measurements which capture the effect of user hand movements at 1900 MHz are incorporated into simulations of a two stage adaptive self-interference canceller, which simulates an electrical balance duplexer and a second stage of digital cancellation with different tracking adaptation rates. Results demonstrate that the dynamic self-interference channel which results from user movement places demanding requirements on the canceller coefficient tracking. Adaptation intervals of the order of tens of microseconds are required to maintain Tx-Rx isolation of the order of 90 dB, calling into question the feasibility of IBFD handheld devices.**

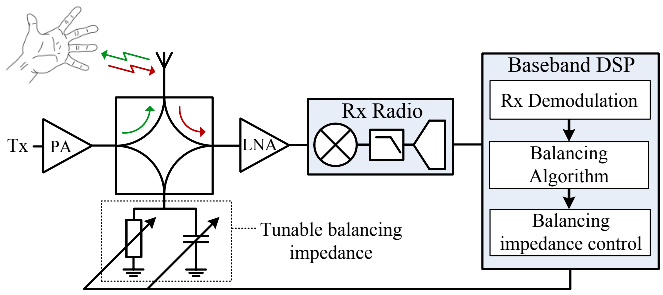


Fig. 1. Electrical balance duplexer with adaptive tracking in order to track antenna impedance changes.

I. Introduction

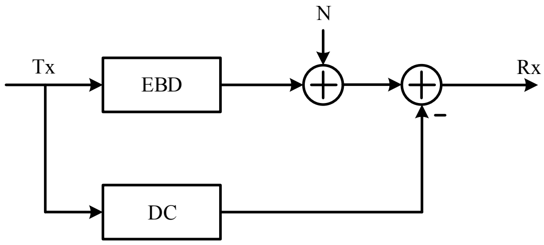
In-band Full-duplex (IBFD) systems, which simultaneously transmit and receive in the same frequency band, have the potential to double link capacity compared to time-division duplexing and frequency division duplexing, as well as reducing latency and solving the hidden node problem [1]. However, in order to achieve IBFD operation, the self-interference (SI) caused by ones own transmission must be suppressed to the receiver noise floor. Transceiver architectures which avoid and/or cancel self-interference have been the subject of substantial research efforts over recent years, with systems typically comprising multiple stages of SI cancellation, combining radio frequency methods (e.g. IBFD antenna designs and passive and active radio frequency (RF) cancellation loops), and digital baseband cancellation (often non-linear), to achieve the required transmit-to-receive (Tx-Rx) isolation, which may be in excess of 100 dB.

The effectiveness of a self-interference canceller is dependent on the accuracy of the cancellation filter coefficients, be those hardware tuning parameters in the case of passive feedforward RF cancellers, or digital coefficients in the case of digital cancellers. Furthermore, in dynamic environments, canceller coefficients may need to be dynamically updated to maintain accuracy as the SI channel varies. This is particularly relevant to handheld devices, where the close proximity of the user's hands can cause substantial changes in the local propagation environment, having a large impact on the self-interference channel. Electrical balance duplexers [2]–[6], which implement passive feedforward cancellation by electrically balancing the antenna impedance with a tunable *balancing impedance*, have been shown in previous works to be sensitive to fluctuations in the antenna impedance caused by reflections from the environment [4], [7]. The tunable impedance is therefore required to be adaptive, as shown in Fig. 1. Previous works [4], [7] have investigated the resulting fluctuations in Tx-Rx isolation in vehicular and user interaction scenarios, and results have shown that the dupelexer must be re-balanced at intervals of the order of 10s of milliseconds in these dynamic environments in order to maintain cancellation of the order of 50 dB (or implement antenna impedance tracking with an equivalent tracking loop bandwidth [6]). The impact of user interaction on Tx-Rx isolation was shown to be particularly significant [4].

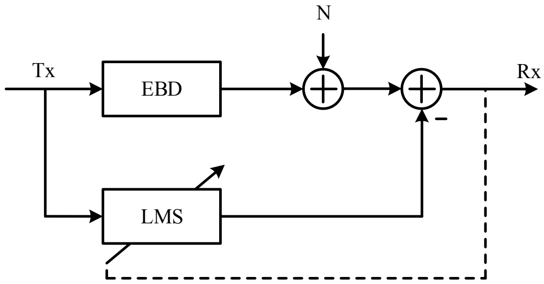
It is notable that where the level of Tx-Rx isolation is higher, the required accuracy of the canceller coefficients is also correspondingly higher, and thus the system will be more sensitive to changes in the SI channel. Therefore, the tuning requirements of the latter stages of cancellation, for example a final stage of digital cancellation, will be more demanding that those of the first stage of SI cancellation. Despite this, to the authors' knowledge, the impact of SI channel variation on the latter stages of SI cancellation has not yet been investigated. To address this, this paper models the impact of user interaction on a two-stage SI canceller which combines electrical balance duplexer (EBD) with a further stage of digital cancellation. A simulated SI canceller with embedded dynamic antenna reflection coefficient measurements from a mobile device texting/browsing scenario is used to determine the impact of the antenna impedance variation on Tx-Rx isolation and develop specifications for canceller adaptation. Results show that the SI channel dynamics have a substantial negative impact, imposing potentially impractical tracking requirements in order to maintain isolation. Because of this, achieving the required levels of isolation for IBFD operation may not be feasible in this type of dynamic environment.

(a) (b)

Fig. 2. (a): Multi-band cellular antenna used in this work, and (b): The same antenna enclosed in a mobile phone housing.



(a)



(b)

Fig. 3. Signal models for (a) the idealised digital canceller and (b) the LMS based digital canceller.

The remainder of this paper is organized as follows: Section II describes the antenna measurements and canceller simulations, section III presents and analyses results, and section IV concludes.

II. Dynamic antenna measurements and simulated SI cancellation

Dynamic antenna reflection coefficients measurements form the basis of the analysis presented in this paper. A Taoglas PAD710 multiband cellular antenna was mounted within a plastic mobile phones housing, as shown in Fig. 2. The antenna reflection coefficient frequency response was then measured periodically at a sampling rate of 1.25 ms whist a person was holding the mobile phone housing and moving their fingers to emulate texting and browsing movements. Data was captured over a duration of approximately 10s. The measurement instrument used was an Agilent N5242 PNA-X vector network analyser (VNA), configured to measure the antenna S_{11} across a 20 MHz bandwidth at 1900 MHz with a frequency resolution of 500 KHz. This measurement dataset therefore comprises a time-series of antenna S_{11} frequency responses, capturing the dynamic change in the antenna reflection coefficient over the frequency band of interest. This measurement of mobile device antenna dynamics is similar to that described previously in [4].

A. EBD circuit simulation

The 1.25 ms antenna reflection coefficient sampling interval provided the VNA was limited by the sweep speed and processing delay of the instrument, however, for the purpose of this simulation, a much faster sample rate is required in order to allow for the analysis of fast tracking loops. To allow for this, the data were interpolated to a higher sampling rate of 100 kHz. The interpolated time-frequency antenna reflection coefficient data were incorporated into a two stage SI cancellation simulation. The first stage is an EBD circuit simulation of the type previously described and validated against hardware measurements in [4], [7], and a detailed description can be found in [8, Section II.B]. This simulates a symmetrical lossless hybrid junction with a single pole resistor-capacitor (RC) balancing network, calculating the Tx-Rx amplitude frequency response, G_{EBD} using the following equation:

$$G_{EBD}(k, nT) = \frac{1}{2}(\Gamma_{Ant}(k, nT) - \Gamma_{RC}(k, nT)) \qquad (1)$$

where n is an integer time index and nT are the sampling instances at period T (10 us), k is a frequency index corresponding to the VNA measurement frequency points, $\Gamma_{Ant}(k, nT)$ is an antenna reflection coefficient measurement from the VNA, and $\Gamma_{RC}(k, nT)$ is the simulated balancing reflection coefficient of the RC balancing impedance network, calculated using standard circuit theory and assuming ideal lumped element components. In this simulation, the simulated balancing reflection coefficient is updated at 5 ms intervals. This periodically re-balances the EBD to maximise Tx-Rx isolation across the band, thereby tracking antenna impedance variations. In the simulation, which runs with a 10 us sampling interval, this corresponds to updating the balancing parameters every 500 samples.

B. Idealised digital canceller

Two different digital cancelling strategies are used as the simulated second staged of cancellation: an idealised digital canceller and a least mean squares digital canceller. Like the EBD simulation, the idealised digital canceller (DC), shown in Fig. 3a, assumes that the canceller coefficients are periodically updated at a given interval; This canceller therefore achieves perfect cancellation down to the noise floor at the time at which the coefficients are updated, but as with the EBD, the level cancellation deteriorates as the SI channel changes, until the point that the coefficients are updated again. This simulation therefore corresponds to a digital canceller which periodically

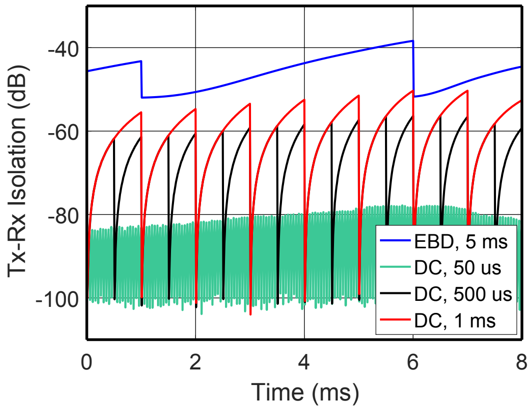


Fig. 4. The Tx-Rx isolation provided by the EBD (5 ms re-balancing interval), and the idealised digital cancellation for coefficient update intervals of 50 us, 500 us and 1 ms. Quantities are integrated isolation across the 20 MHz band.

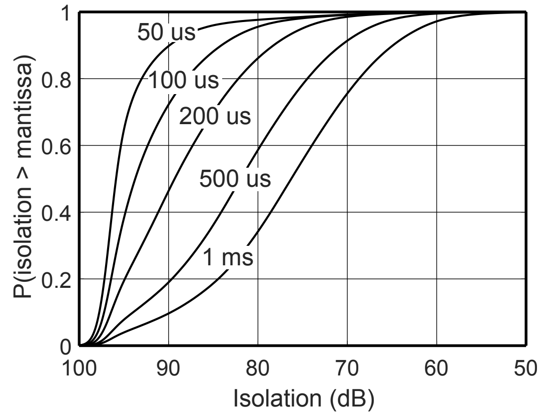


Fig. 5. Cumulative distribution functions of the Tx-Rx isolation after idealised digital cancellation for different coefficient update intervals.

updates the coefficients by directly calculating of SI channel from the Tx and Rx waveforms in the digital domain. The noise floor in this simulation corresponds to a Tx-Rx isolation of -100 dB. The simulation calculates the Tx-Rx transfer function after idealised digital canceller, G_{IDC} as:

$$G_{IDC}(k,nT) = G_{EBD}(k,nT) - G_{EBD}(k, R\left\lfloor\frac{n}{R}\right\rfloor T) + N(k,nT) \quad (2)$$

where $N(k,nT)$ is Gaussian random noise and R is adaptation interval (i.e. the number of samples between coefficient updates), and $\lfloor . \rfloor$ is the floor operator, such that the canceller is updated at the time instants given by $R\lfloor\frac{n}{R}\rfloor T$.

C. Least mean squares adaptive digital canceller

Digital cancellers based on iterative optimisation have also been widely studied [9], [10]. To investigate the tracking performance of a typical iterative canceller a user interaction scenario, a least mean squares (LMS) based digital canceller has also been implemented (in place of the idealised digital canceller), as shown in Fig. 3b. This canceller uses the standard LMS algorithm with a fixed step size of μ=0.4 (manually optimised for this simulation). Unlike the above mentioned simulation, which can directly calculate the Tx-Rx isolation, the operation of the LMS algorithm requires a Tx signal to be simulated in order that input signals can be fed to the LMS canceller. For the purpose of the simulation, the Tx signal is a Gaussian random noise signal (i.e. similar to an orthogonal frequency-division multiplexing (OFDM) signal in the time domain) with a sample rate of 20 MHz. In this simulation, the Tx signal was set to 0 dBm, such that the resulting residual interference power in dBm is equivalent to the Tx-Rx isolation in dB, thus allowing the results of both digital canceller simulation to be directly compared. The noise floor in this simulation is -100 dBm.

III. Results

A. EBD with idealised digital canceller

Fig. 4 shows the Tx-Rx isolation provided by the EBD, and by the EBD and digital canceller together for three update intervals over a relatively short 8 ms time period, thus allowing the details of tracking behaviour to be observed. For the longer update intervals of 500 us and 1 ms the digital cancellation performs poorly, with the Tx-Rx isolation often going as low as -60 dB. Even with a much smaller update interval of 50 us, it is notable that the cancellation is degraded by as much as 20 dB between updates, showing that the user interaction can have a substantial negative impact on cancellation performance.

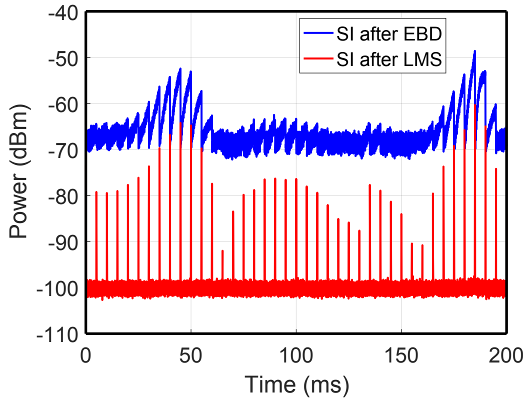
Fig. 5 shows the cumulative distribution function (CDF) of the Tx-Rx isolation after idealised digital cancellation across the full 10 seconds of user interaction data. For the 50 us update interval, >90 dB Tx-Rx isolation is achieved for ~90% of the time. The slower updating simulations demonstrated substantially worse performance; for the 1 ms update interval, >90 dB Tx-Rx isolation is achieved <10% of the time, and at times the digital canceller provides only a few dB of cancellation.

It is pertinent to consider that updating the canceller coefficients at intervals of 50 us represents a substantial processing overhead, and therefore these results would suggest that achieving such high levels of isolation may be impractical when the system is subject to this type of dynamic self-interference.

B. EBD with LMS canceller

Fig. 6 shows the residual SI power after the EBD and after the LMS canceller for two different LMS adaptation intervals. In Fig. 6a, the LMS adaptation is occurring on every sample of the SI signal (i.e., every 50 ns). This shows good tracking performance, but exhibits spikes in SI when the EBD balancing impedance retunes. At those instants there is a step change in the SI channel due to the EBD re-balancing, and as shown in Fig. 7 the LMS algorithm takes an approximately 50 us to re-converge. In Fig. 6b, the LMS canceller is adapting every 25 us; this also shows spikes in SI due to the EBD re-balancing, but the time taken to re-converge is much longer. Furthermore, the tracking of the SI channel variation is substantially degraded, impacting on the level of cancellation by as much as 30 dB compared to the 50 ns tracking.

Fig. 8 shows CDFs for the residual SI power after LMS cancellation for various update rates. It can be seen that a



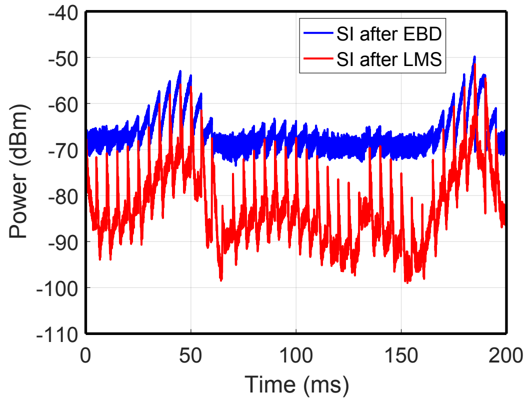


Fig. 6. Residual SI power after the EBD and after the LMS canceller, for two different LMS update intervals: (a) 50 ns and (b) 25 us

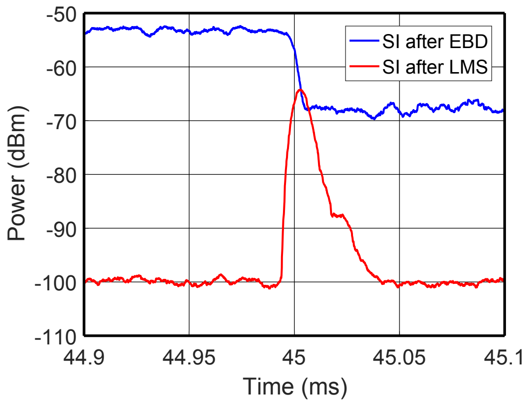


Fig. 7. Convergence time of the LMS canceller with 50 ns update interval.

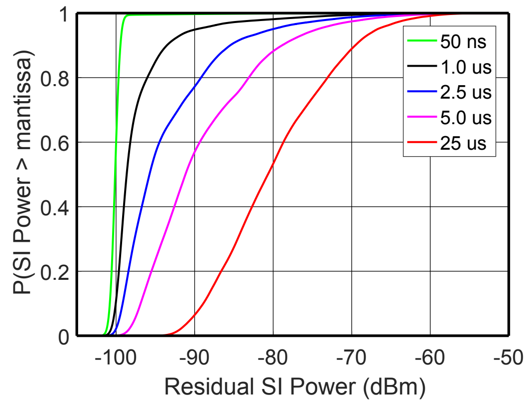


Fig. 8. CDFs of the redisual SI power after LMS canceller for different coefficient update intervals.

tracking interval of 1 us is required to maintain cancellation close to the noise floor (i.e., -100 dBm). As with the idealised digital cancellation, this tracking rate may be impractical due to the associated processing, calling into question the feasibility of IBFD in handset devices when subject to the effects of user interaction.

IV. Conclusions

High levels of self-interference cancellation require correspondingly high accuracy in the coefficients of the SI cancellers. SI cancellers must therefore adaptively track changes in dynamic SI channels, and small errors may impact on the canceller performance.

This paper has investigated the effect of electromagnetic interaction between the user and antenna in handheld IBFD transceivers utilising electrical balance duplexers as the first stage of cancellation. Dynamic antenna reflection coefficient measurements from a user interaction scenario at 1900 MHz have been embedded in SI canceller simulations in order to investigate the impact of SI channel fluctuations and develop specifications for canceller coefficient tracking. Results show that the user interaction scenario places extremely demanding requirements for coefficient tracking on the digital canceller; maintaining isolation of the order of 90 dB requires coefficients to be updated at intervals of the order of tens of microseconds. This casts doubt upon the feasibility of EBD based IBFD in handheld devices.

Acknowledgment

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